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GEOLOGICAL SURVEY BULLETIN

No. 7

GLACIAL LAKE AGASSIZ, WITH SPECIAL
REFERENCE TO THE MODE OF
DEFORMATION OF THE
BEACHES

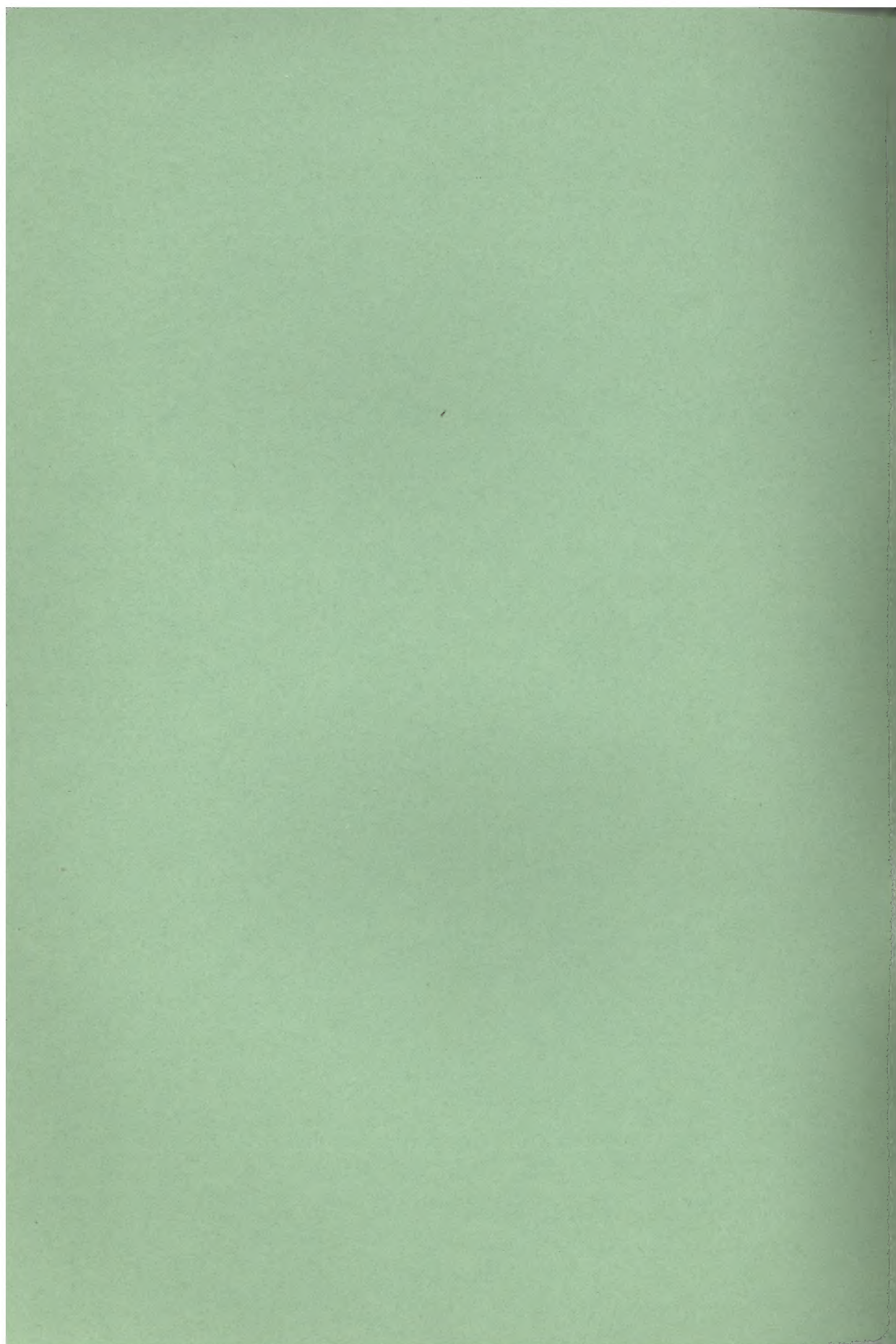
BY

W. A. Johnston



OTTAWA
EDMOND CLOUTIER, C.M.G., B.A., L.Ph.,
KING'S PRINTER AND CONTROLLER OF STATIONERY
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PREFACE

Glacial Lake Agassiz, made famous by the pioneer geological work of Warren Upham more than 50 years ago, covered an area in north-central North America that was nearly as large as the combined areas of the Great Lakes. Its deposits of silt and clay form the fertile soils of Manitoba and adjacent regions; and the sand and gravel deposits of the lake beaches are an important source of structural materials. Moreover, the moraines marking the former ice borders of the lake, and the beaches, are of importance in locating and constructing roads in the undeveloped northern parts of the lake basin. Studies of the ancient lake, therefore, are of value, not only for their scientific and popular interest, but in many other ways.

The present study summarizes the previously unpublished work done by the author at various times from 1912 to 1929, and deals particularly with the mode and amount of uplift of the land in the lake basin. In order to determine the character of the uplift it was necessary to take into consideration the results of studies of Lake Agassiz in Minnesota and in the Dakotas by other geologists, particularly Frank Leverett, as well as Upham's original work, and the work done in Canada in more recent years by the author and by other geologists.

GEORGE HANSON.

Chief Geologist, Geological Survey.

OTTAWA, January 30, 1946

GLACIAL LAKE AGASSIZ, WITH SPECIAL REFERENCE TO THE MODE OF DEFORMATION OF THE BEACHES

INTRODUCTION

Mapping of many of the glacial Lake Agassiz beaches in Manitoba and adjacent parts of Saskatchewan and Ontario has been done by the writer, and elevations of the beaches have been determined at many places. The results of this work, taken in conjunction with the work of Upham and Leverett in the more southerly parts of the lake basin, have made possible the drawing of isobases¹; and by means of a profile of the beaches drawn perpendicular to their isobases² it is now possible to determine, at least to some extent, the mode and amount of deformation of the beaches, and in this way to show approximately the mode and amount of uplift of the land in the region formerly occupied by glacial Lake Agassiz.

Upham extended his mapping of the Lake Agassiz beaches in the Dakotas and in Minnesota northward into Manitoba as far as the latitude of Gladstone(24)³. In his monograph(25) he gives, in addition to the results of his own work, an account of related work by many geologists, including that by J. B. Tyrrell (20, 21, 22), whose mapping and elevations of beaches in north-central Manitoba were used by Upham in correlating the beaches north of Gladstone with those to the south.

Leverett revised a large part of Upham's work in the Dakotas and in Minnesota, and together with F. W. Sardeson, the results of whose work are included with Leverett's in a Professional Paper (13), added much detailed mapping of moraines and beaches.

In preparing the present report the writer has used much information found in the above-mentioned reports. Information from other reports, references to which will be given later, has also been used; and the writer is indebted to S. C. Ellis⁴ for obtaining elevations of two beaches west of Chemong in the Pasqui Hills in eastern Saskatchewan, and to F. J. Alcock⁴ for the elevations of three beaches on the portage between Reed and File Lakes in northern Manitoba.

The mode of uplift of the glaciated regions in late Glacial and post-Glacial times has long been a subject of debate. The main point in dispute appears to be whether warping on a large scale or only tilting of blocks of the earth's crust occurred. The great strength of the earth's outer shells(4) seems to preclude the theory of warping, except at hinge lines, under the moderate stresses caused by relief from the load of the ice-sheet; but if it can be shown that only vertical uplift and tilting of blocks bounded by hinge lines occurred, this objection to the isostatic theory of recovery from the ice load may be largely removed. The Lake Agassiz beaches are especially favourable for the

¹ Isobases are lines connecting points of equal deformation of old water planes, as shown by equal elevations of the beaches or other features that form records of the water planes at these points.

² In this report all points on the isobases that are well defined are considered to have been equally deformed, and the term "isobases of the beaches" is used instead of a longer descriptive term such as "isobases indicating the position of the old water planes in their present deformed state."

³ Numbers in brackets are those of references cited at end of this report.

⁴ Personal communication.

study of this question; they form a fairly complete record of earth crustal movements in the lake basin throughout late Glacial time; they number about fifty, and some of them have been traced in the direction of tilt for more than 300 miles.

Other problems in connection with the life history of the lake are the location of the ice borders at various stages, the location of outlets after abandonment of the southern outlet, and correlation with events in other glaciated regions. Some of the ice borders in northern Manitoba and adjacent parts of Ontario have been described by Antevs(1) and correlated with ice borders in Ontario and Quebec. These problems are only lightly touched on in the present report. The possible location of some of the outlets, other than the southern outlet, as suggested by the elevations and trends of the beaches, is briefly discussed; and several beaches not recorded by previous workers are named and described.

Field work by the writer was done at various times from 1912 to 1929, but as the work was incomplete no detailed reports have been made except on local areas (8, 9, 10). A map on 1 inch to 8 miles, showing the surface deposits of a large part of southern Manitoba and adjacent parts of Saskatchewan, has been published(11). The writer hoped to have obtained the elevations of beaches, and to have traced the moraines in the area along the Canadian Pacific Railway east of Lake of the Woods to the height of land, and north to Sioux Lookout. This area is of special importance. Elevations of the beaches would show whether tilting was at the same rate there as it was in northwestern Manitoba, as is assumed in the present report; two or more ice borders in the area are marked by moraines(14, 15, 16); and the area probably is the locus of some of the outlets that drained the lake eastward. Moreover, in the vicinity of Sioux Lookout glacial till overlies varved clay, indicating a readvance of the ice-sheet(7). It may be possible to correlate the clay overlain by till with the Lake Agassiz clays to the west, and thus to date the readvance of the ice. It proved impossible for the writer to do this work, and the present report is made in order to set forth the present conclusions, and to indicate what further work in Canada is required. A study of the figures accompanying this report will show that much more tracing of the beaches and moraines must be done, and more elevations of the beaches obtained before the history of the lake is completely known.

The writer is indebted to Dr. Ernst Antevs for good advice.

DESCRIPTION OF THE BEACHES

In the southern part of the lake basin there are four beaches, or rather four series of closely spaced beaches, connected with the southern outlet. The outlet was cut down about 90 feet during the period of southward outflow (25, p. 225; 13, p. 126). These beaches as named by Upham (25, pp. 276, 277) are; from highest to lowest, the Herman, Norcross, Tintah, and Campbell. To the north the Herman beach splits to form, according to the writer's mapping, twelve or thirteen strands. Upham recorded only seven (25, pp. 476, 477). Most of the beaches are poorly developed in the north along the eastern slopes of Riding and Duck Mountains. The entire series was not found at any one place, but occurrences at different places indicate that there are at least twelve shorelines. Splitting of the Herman beaches appears to have taken place at two hinge lines, 60 and 120 miles respectively north of the outlet, and at the first hinge line a few miles south of the outlet.

The Norcross beach is a series of four closely spaced shorelines, or two main shorelines (25, p. 388). They are parallel or show only slight divergence throughout their course.

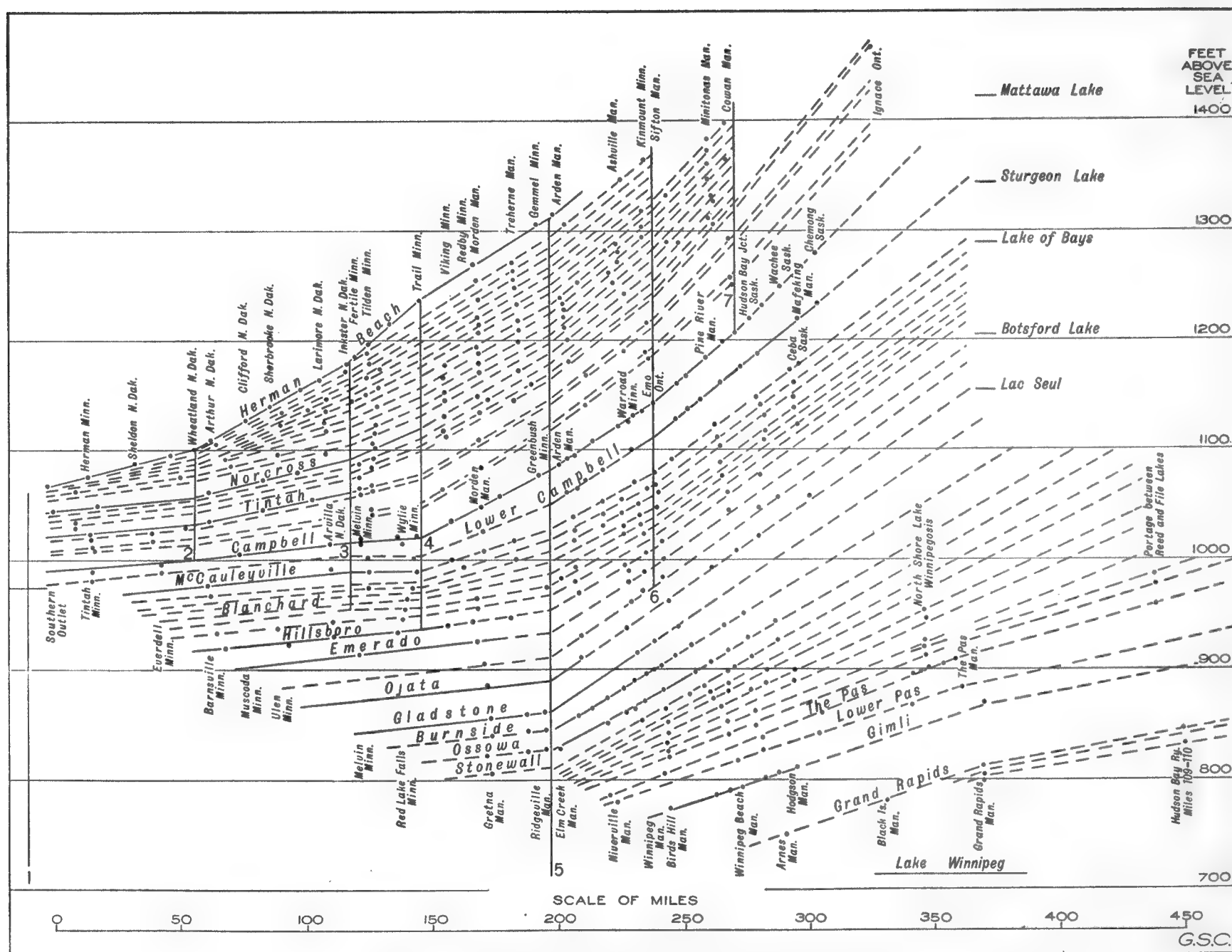


Figure 2. Profile showing present position of glacial Lake Agassiz beaches.

The Tintah shoreline consists of two pairs of beaches, or two main shorelines (25, pp. 397, 398), which do not split to form other strands but show wide divergence to the north.

The highest Herman (Figure 1) and Norcross, and the Tintah beaches are especially well developed, and have been traced for long distances. The other beaches (See Figure 2) have been "fitted in" according to their elevations and relationship to known beaches above and below them.

The Campbell beach is uniformly and strongly developed in the north and in the south. In many places it is a ridge or series of ridges containing 25 to 30 feet of sand and gravel, and is one-quarter mile to more than a mile wide. So far as known the beach does not split to the north, but the individual strands may show some slight divergence. The beach has been interpreted by the writer (9) as marking a return of drainage of glacial Lake Agassiz to its southern outlet after the lake had been temporarily drained eastward, and this temporary outlet had been closed by a readvance of the ice-sheet. The main evidence for this conclusion is that a marked unconformity occurs in the Lake Agassiz deposits in the southern part of Lake of the Woods. The depositional break is there about 60 feet below the level of the Campbell beach, and extends upward to the level of the beach or to one of its members.

The Lower Campbell beach differs in character and mode of development from the Campbell; it is well developed in the north and poorly developed in the south. It is shown on Figure 2 as the lowest shoreline connected with the southern outlet, but this is uncertain. It may coincide, for some distance north of the outlet, with the lowest beach of the Campbell series, about 10 feet below the highest or main beach, or it may not be connected with the southern outlet. Only the main beach, the Campbell, is shown on Figure 2. The Lower Campbell beach began to be formed after the lake fell about 60 feet—the vertical interval between the Campbell and Lower Campbell beaches in the region of the eastern outlets—owing to retreat of the ice-sheet and uncovering of an outlet that was lower than the southern outlet. Differential uplift started when the beach began to be formed, or at a somewhat later time, being greater in the north than in the south. This is shown by the fact that the beach is not parallel to the Campbell, but converges towards the south. There was no appreciable uplift during lowering of the lake level, as the lake must have fallen very rapidly. The Lower Campbell beach thus marks the upper limit of a transgressive shoreline.

The highest McCauleyville beach, the next lower one, also marks the upper limit of a transgressive shoreline. Differential uplift continued during its formation, except during the final stage; its considerable strength in the south shows that the lake stood at the level of the beach for some time. Upham interpreted the beach as having connection with the southern outlet, but Leverett has pointed out (13, p. 139) that this is extremely doubtful.

The three other McCauleyville beaches, and a series of lower shorelines, including the Blanchard, Emerado, Ojata, and Gladstone, are very nearly parallel. They are normal shorelines formed during a long period of comparative stability, when the lake was being lowered by the cutting down of one or more outlets to the east and by the opening of new outlets at progressively lower levels due to retreat of the ice-sheet. A small amount of land sinking, referred to in a later part of this report (page 15), took place during the first part of the period. All these beaches, and the Burnside, Ossowa, and Stonewall at lower levels, were named and described by Upham. Fortunately, he has given in his monograph a good record of them, together with many accurate elevations, for some of the beaches in southern Manitoba cannot now be traced owing to the effects of soil drifting and erosion. The writer checked many of Upham's elevations and found only slight differences. The writer's

mapping and correlation of beaches (Figure 2), including the McCauleyville and lower shorelines down to the Ossowa, are substantially in agreement with Upham's mapping and correlation. There are a number of shorelines, however, below the Ossowa that were not noted by him, probably because the region in which they occur was largely wooded or swampy, and was not easily accessible at the time of his work. Upham recorded (25, pp. 476, 477) only one Stonewall beach and two other beaches below the Ossowa. There are, however, seven or eight shorelines that may be considered as belonging to the Stonewall series. Below these are two beaches here named the Pas beaches. The upper one was traced for 20 miles along the railway from Westray north to The Pas. In this stretch the beach is practically continuous except for a break about midway, near Freshford (possibly the beach splits near Freshford; if so there should be two beaches north of The Pas). The lower beach occurs west of the higher one near The Pas. They probably correlate with the two beaches near Niverville, 20 miles southeast of Winnipeg, which Upham named the Niverville beaches. He regarded them as the lowest series of the Lake Agassiz beaches, and correlated them with a series at Grand Rapids, near the mouth of Saskatchewan River (25, pp. 471-473). As they are not the lowest beaches and do not correlate with the beaches at Grand Rapids they are here renamed the Pas.

Below the Pas beaches is a single strong shoreline here named the Gimli, from the name of a town on the west side of Lake Winnipeg near which the beach is well developed. It was traced for about 30 miles in the area west of the lake, and continues, in a less definite form, to the vicinity of Winnipeg. It is the lowest beach at Birds Hill, 7 miles northeast of Winnipeg, and has been mapped only approximately in the area southeast of Lake Winnipeg. Near Grand Beach and Beaconia, on the southeast shore of the lake, the beach is well developed. In this area there were a number of islands in the lake at that stage; the main shore lay farther to the southeast, and extended northeast from Birds Hill to near Great Falls on Winnipeg River. Its extent farther to the east is not known.

The lowest series of Lake Agassiz beaches in the Lake Winnipeg region is here named the Grand Rapids. They are known at only a few places. The writer found one at Arnes on the west side of Lake Winnipeg. Tyrrell recorded (21, p. 25; 25, p. 472) a beach, which probably belongs to this series, on Black Island, about 60 feet above the level of Lake Winnipeg. He also recorded three beaches, which belong to this series, at Grand Rapids. A higher beach noted by Tyrrell at this locality probably is the Gimli. Two beaches on the Hudson Bay Railway, 109 and 110 miles respectively from The Pas, probably are Grand Rapids beaches, as they are the lowest Lake Agassiz beaches known anywhere in the lake basin. The lowest of the three beaches reported by Alcock, on the portage between Reed and File Lakes north of The Pas, may be the upper Pas beach; and the other two may belong to the Stonewall series. The lower Pas and Gimli beaches, if the above suggested correlations are correct, have not been noted along the Hudson Bay Railway, nor at other places in this general region.

Upham's correlation of the beaches at Niverville with the lower beaches at Grand Rapids indicated that only slight changes of level were shown by the attitude of the lowest series of Lake Agassiz beaches (25, p. 487). On the contrary, the lowest series in the Lake Winnipeg region has a relatively high tilt rate. This is an important point, and is referred to later (page 16) in connection with the problem of uplift.

The Burnside and the lower beaches down to and including the Pas are records of transgressive shorelines; they converge towards the south. Some of

them split to form other shorelines in the north. The lower Pas, Gimli, and Upper Grand Rapids on the other hand are nearly if not quite parallel; they were formed during a period of stability of the land.

There is a depositional break in the Lake Agassiz sediments below the level of the Gimli beach. It is well shown in a section on the west bank of Red River one-quarter mile below Redwood bridge in the city of Winnipeg, and at lower levels, notably in a section in a ditch along an east-west road near Brokenhead post office, about 45 miles northeast of Winnipeg. It seems probable, therefore, that the lake was temporarily drained by the uncovering of one of the lowest outlets by the retreating ice-sheet, and that it was later raised to the level of the Gimli beach by a readvance of the ice, which again blocked the outlet.

ELEVATIONS OF THE BEACHES

The beach elevations used in this report are from various sources. Most of those in Minnesota and the Dakotas are given in Leverett's Professional Paper 161. Some, including those referred to above, and a few others at points near Barnsville and Dorothy, Minnesota, and in North Dakota, are from Upham's monograph. A number of elevations in Manitoba, including those near Treherne, Gladstone, Arden, and Niverville, are by Upham, and are given in his monograph. He also quotes a number of elevations given by Tyrrell. These include elevations of beaches on Black Island in Lake Winnipeg, at Grand Rapids, and on the eastern portage between Lake Winnipegosis and Cedar Lake. Other elevations in Manitoba and adjacent parts of Ontario and Saskatchewan are by the writer, except the elevations of the two beaches west of Chemong, determined by Ells, and of the three beaches on the portage between Reed and File Lakes obtained by Alcock. Nearly all of them are elevations, in feet above sea-level, of the crests of beach ridges, and were made by levelling to or from bench marks or other features, whose elevations had been determined by precise levelling (*See Altitudes in Canada by James White, Commission of Conservation, Canada, 1916; and Precise Levelling in Canada by the Geodetic Survey*). Elevations of cut terraces, the bases of old shore cliffs, were made at only a few places where beach ridges were absent, and as a rule they are not so reliable in determining the ancient lake levels as are the elevations of the beach ridges. The elevation at Ignace, Ontario, is the upper limit of lake sands, and does not mark any definite beach. The elevation of the Gimli beach, near Beaconia on the southeast side of Lake Winnipeg, is estimated from the contoured map, on 1 inch to 4 miles, of the Selkirk area, by the Surveys and Engineering Branch, Department of Mines and Resources, Ottawa, Canada.

Elevations of the beaches at Grand Rapids were determined by the writer by levelling from the highest beach near the western end of the portage tramway to Lake Winnipeg. The highest beach, which probably is the Gimli, has an elevation of 869 feet above the sea, 19 feet higher than that reported by Tyrrell (21; 25, p. 471). Two lower beaches, the Grand Rapids, have elevations of 813 and 809 feet respectively, nearly the same as that reported by Tyrrell if the difference in elevation of the lake be taken into consideration. The lake has a mean elevation of 714 to 715 feet, whereas Tyrrell considered it to be 710 feet. A third beach 10 feet lower was reported by Tyrrell. It was not noted by the writer, but no special search was made for it; it may have been destroyed along the tramway of the portage by removal of the gravel.

Elevations of beaches in the Rainy River district, Ontario, some of which are shown on Figure 1, are given in a report by the writer (8). All of them, except the two highest at 1,177 and 1,200 feet, probably Tintah shorelines, are Campbell or Lower Campbell beaches. At the time the work was done only a

few of the beaches were thought to belong to the Campbell series. Some of the Campbell strands below the highest main beach show evidence of erosion by wave action or are partly buried beneath silt; they appear to have been formed during a rising stage of the lake. They were not found except locally in the wider, open parts of the lake basin. In places, for example between Ashville and Ethelbert in western Manitoba, there are beach ridges, 8 to 10 feet below the main Campbell beach, that appear to have been formed before the main beach was built. Leverett has pointed out (13, p. 138) that in places in Minnesota a series of beaches marks the Campbell shoreline, whereas at other places there is only one main ridge.

A beach on the north side of Rainy River, 3 miles below Fort Frances and International Falls, has an elevation of 1,131 feet, 15 feet above the level of Rainy Lake. It probably is the Lower Campbell beach. Another 4 miles to the southwest at 1,145 feet is probably the main Campbell beach. These occurrences show that an embayment of Lake Agassiz at the Campbell stage extended well to the east of Rainy Lake. The presence of varved clays in the area east of the lake as reported by T. L. Tanton of the Geological Survey (personal communication) bears out this conclusion. The conjectural position of the Campbell shoreline in this area is shown on Figure 1. The Campbell shorelines near Dryden and southwest of Eagle Lake, as shown on Figure 1, are also conjectural.

The altitude of the Campbell beach west of Red Lake Falls in Minnesota is slightly less than it is farther south, as was noted by Leverett (13, p. 138). The lower beaches down to the Hillsboro also appear to show less tilt in this area than they do farther south. On the west side of the lake there probably is a similar decrease in the rate of tilt of the Campbell beach. Near Arvilla the altitude of the beach is 1,014 feet, and 2 to 3 miles to the north it is a few feet lower (25, p. 418). Farther north near Inkster "the Campbell shore is a low escarpment in the general surface of till, with crest at 1,018 to 1,026 feet, from which there is a somewhat steep descent of 15 to 25 feet" (25, p. 419). Still farther north at Park River "the Campbell escarpment falls rather abruptly from 1,035 feet to 1,015 feet above the sea" (25, p. 419). The true level of the beach, therefore, may be nearly the same at Park River as at Arvilla, and probably is slightly lower at Inkster. The Campbell "embankment" near Tongue River, 25 miles north of Park River, has an elevation of 1,020 to 1,030 feet in the course of 6 miles south of the river (25, p. 420), thus indicating a rapid rise similar to that found on the eastern side of the lake.

The higher rate of rise of the highest Herman beach in Minnesota, in the vicinity of the place where the beach turns from a northward to an eastward course (13, p. 133), also appears to occur on the western shore in the area immediately south of the north branch of Park River (25, p. 353).

The following elevations of Lake Agassiz beaches in Manitoba, in addition to those shown on Figures 1, 3, 4, and 5, were used in making Figure 2. They are listed according to the localities (Figures 3, 4, and 5) at or near which the elevations were determined, and are given in feet.

Figure 3

1 to 5 miles northeast of Treherne—	1,266, 1,254, 1,245, 1,236, 1,212, 1,197
7 to 9 miles west of Gladstone—	980, 995, 1,030
3 to 4 miles southeast of Eden—	1,236, 1,230, 1,212, 1,200
0 to 1 mile west of Riding Mountain—	1,055, 1,145, 1,265
0 to 4 miles west of McCreary—	991, 1,007, 1,032, 1,041
3 to 5 miles southwest of Makinak—	990, 1,007, 1,022, 1,072
1 and 4 miles east of Ochre River—	925, 900
5 to 8 miles southwest of Ashville—	1,233, 1,263, 1,286
5 to 15 miles west of Sifton—	1,048, 1,062, 1,080, 1,182, 1,213, 1,263, 1,285, 1,295, 1,303

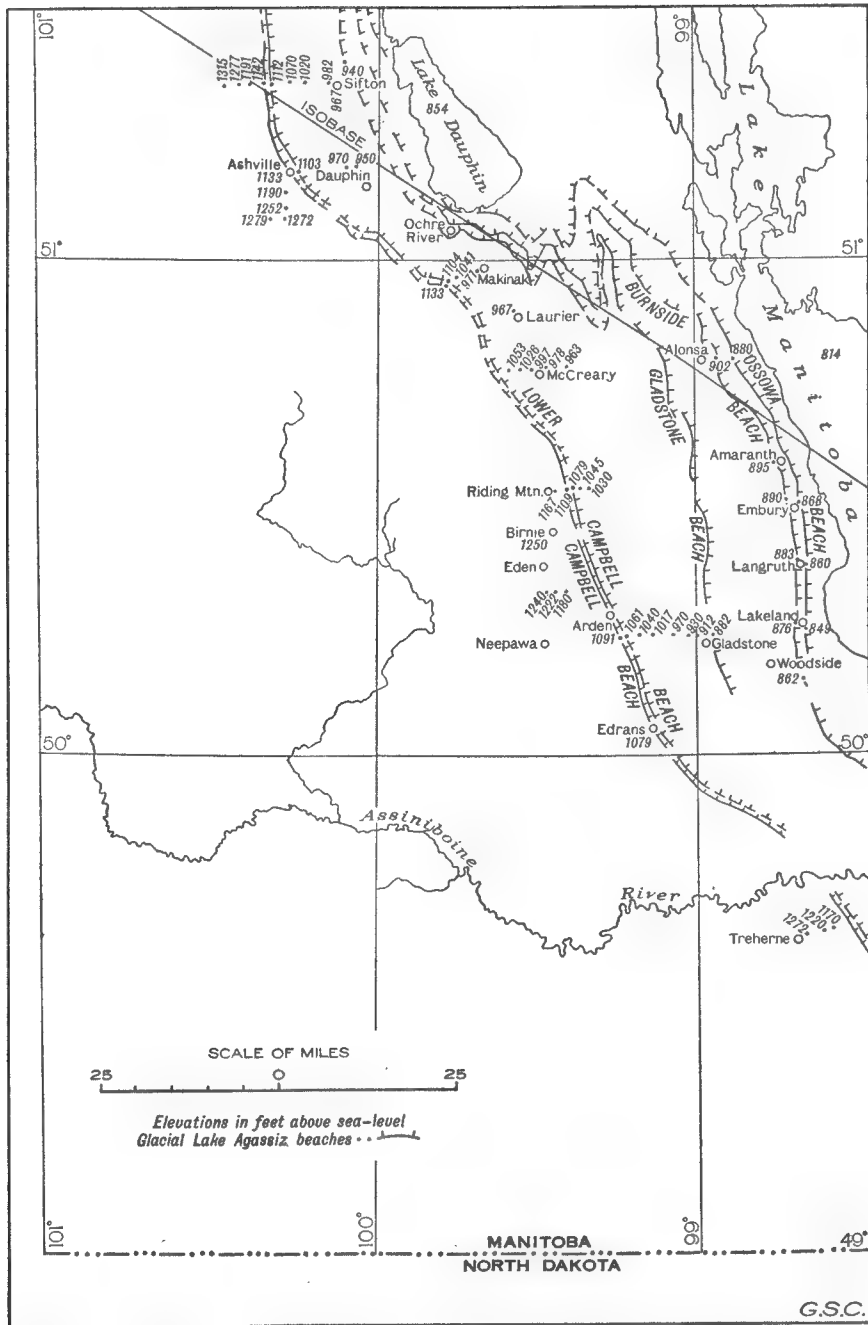


Figure 3. Elevations and isobases of glacial Lake Agassiz beaches in southwestern Manitoba

Figure 4

5 to 6 miles west of Ethelbert—1,287, 1,332
 5 miles southwest of Garland—1,212, 1,291
 Pine River—1,182
 3 miles south of Sclater—1,191; 2 miles west on town line—1,274, 1,328
 3 miles north of Sclater—1,199, 1,164
 1 to 3 miles west of Cowan—1,250, 1,259, 1,292, 1,355, 1,364, 1,395

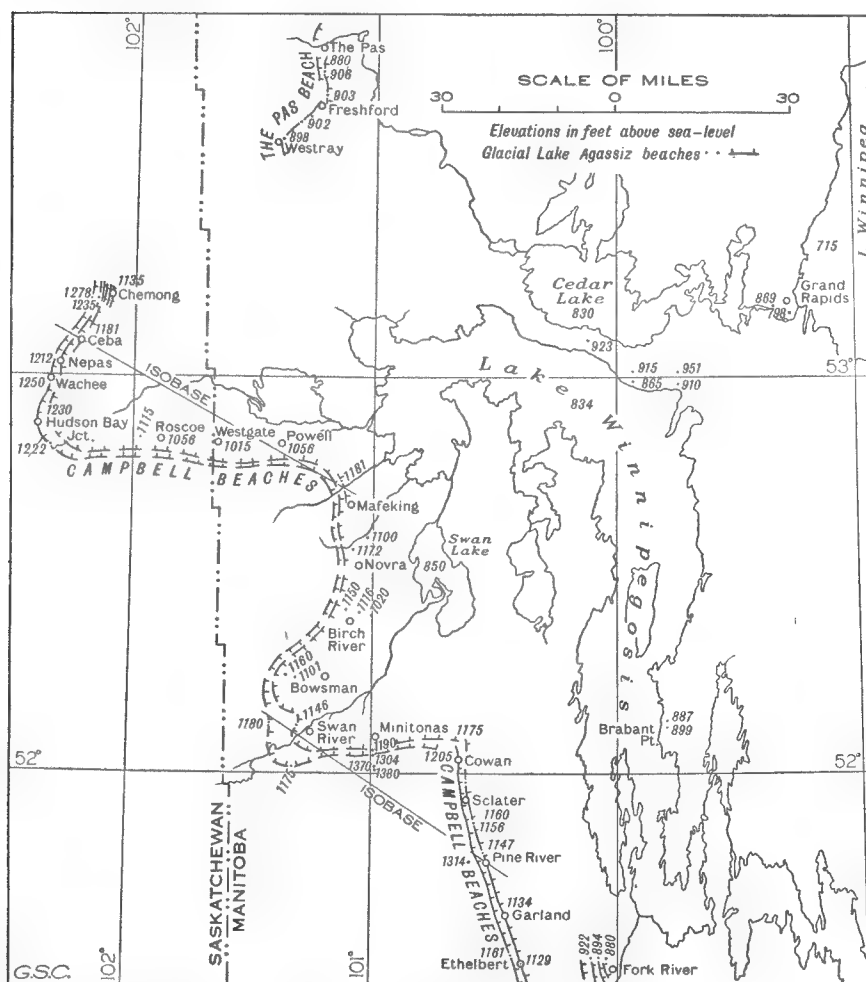


Figure 4. Elevations and isobases of glacial Lake Agassiz beaches in northwestern Manitoba and eastern Saskatchewan.

3 to 6 miles south of Minitonas—1,308, 1,324, 1,347, 1,360
 3 to 6 miles west of Bowsman—1,042, 1,060, 1,080, 1,090, 1,108, 1,122
 0 to 3 miles west of Birch River—1,047, 1,076, 1,107, 1,130, 1,137
 4 miles north of Novra, along Bell River—1,109, 1,120, 1,137, 1,145, 1,161
 3 miles north of Mafeking, at Steeprock River—1,221
 North shore of Lake Winnipegosis—eastern locality, 918, 924, 945; middle locality, 895; western locality (portage) 895
 Grand Rapids, near eastern end of tramway—813, 808

[illegible]

4 and 5 miles southeast of Ridgeville—891, 906
6 miles east of Hazelridge—837
Milner—950
6 and 7 miles west of Winnipeg Beach—814, 825
0 to 3 miles southeast of Spearhill—946, 923, 900, 885

OUTLETS OF LAKE AGASSIZ

After abandonment of the southern outlet a series of progressively lower outlets was opened. Some of them almost certainly were in northwestern Ontario, along the height of land extending from a point on the Canadian Pacific Railway, about 60 miles west of Lake Superior, north to near the western end of Lake St. Joseph. Parts of this region were sufficiently low, when uncovered by the ice-sheet, to have permitted drainage eastward; and, as it was the most southerly part, the ice-sheet probably retreated from this region before it did from any other part of the lake basin that was sufficiently low to have permitted drainage.

Extensive deposits of lake sands and clays have long been known in the Dryden-Wabigoon area along the Canadian Pacific Railway east of Lake of the Woods, and in the Sioux Lookout area to the northeast. According to the writer's observations, the upper limit of the lake sands along the railway is at Ignace, at an elevation of 1,485 feet. There is little doubt that the sands and clays are Lake Agassiz deposits; they are fairly continuous, except in a few high areas, eastward from Lake of the Woods to Ignace; and the areas in which they occur drain westward. Moreover, the chocolate-red varved clays in the Dryden-Wabigoon area, described by Rittenhouse(15) and Satterly(16), or similar clays in a less pronounced form, extend far to the west well into an area that is known to be part of the Lake Agassiz basin. The varved clays in the Sioux Lookout area have been described by Hurst, who regarded them as possibly Lake Agassiz deposits(7). They are at a lower elevation, about 200 feet lower, than that of the clays in the Dryden-Wabigoon area, and were laid down after the ice had retreated from the Eagle Lake moraine (14), and, at a somewhat later time, from the Hartman moraine(15) in the Dryden-Wabigoon area. One or more moraines occur in the Sioux Lookout area, and are especially well developed near Hudson, 12 miles west of Sioux Lookout, and near Zarn, 15 miles to the southeast (7, p. 17 and map). At the time of their formation one or more eastern outlets probably had been opened.

None of the eastern outlets is known from observation. The possible location and approximate elevation of a few, as suggested by the trends and elevations of the beaches, are shown on Figure 2. Mattawa Lake, having an elevation of about 1,420 feet above the sea, is a few feet below Shikag Lake, which is separated from Metionga (Neteianga) Lake, still farther to the east, by the height of land. The elevation of the divide is not known. It probably is at least 1,475 feet above the sea, and this may be too high to have permitted drainage eastward at the Campbell stage, but not at the lowest Tintah stage. Sturgeon Lake, 10 miles to the northwest, has an altitude of 1,342 feet, and is a favourable location for an outlet. The lake extends 30 miles northeast, and drains west, its head being close to the height of land. The area at the head of the lake was about 60 feet lower, relatively to the southwest end, during the Campbell stage than it is now, as is shown by the tilt rate of the Campbell beach. It seems possible that there are passes across the divide that are less than 60 feet above the level of the lake, but this is not definitely known.

The next lower outlet possibly was by way of Lake of Bays, about 10 miles farther to the northwest. This outlet appears to have been cut down gradually; the McCauleyville, Blanchard, and Hillsboro beaches are very closely spaced, and possibly were connected with this outlet. Another lower outlet may have been by way of Botsford Lake and the chain of lakes and rivers extending eastward to the divide a few miles west of Savant Lake. The tilt rate may have been sufficient to have caused reversal of this drainage. At present it is westward.

The lowest possible outlet south of the Patricia highland(23) may have been across the divide between Lake St. Joseph and the headwaters of Lac Seul, or at some other point near there. The elevation of the divide along the tramway near the head of Lake St. Joseph was determined by the Hydro Electric Power Commission of Ontario to be 1,251 feet above the sea. Somewhat lower passes may occur a short distance to the north or to the south. The location and elevation of Lac Seul are shown on Figure 2 as marking the beginning of this possible outlet channel. Taking into consideration the tilt rate, it is possible that the Lac Seul area drained eastward at that time.

There were other lower outlets north and northeast of the Patricia highland, but with the information at hand it is useless to speculate as to their location.

ICE BORDERS OF LAKE AGASSIZ

The ice border during the highest Herman stage of glacial Lake Agassiz is shown approximately by the moraines in the Dakotas and in Minnesota as mapped by Upham and Leverett (See particularly Plate 3 accompanying Prof. Paper 161). Leverett has pointed out (13, p. 134) that the highest beach may not continue into northern Minnesota. On the western side of the lake it probably does not extend as far north as the International Boundary; west of Morden, Manitoba, it appears to be replaced by a narrow moraine extending north and south(11). Lower Herman beaches continue north from Morden to the vicinity of Cowan, though some of them extend only to the broad valley separating Riding Mountain from Duck Mountain. They are absent along the northern slope of Duck Mountain, but appear again in the valley of Swan River to the west. Along the eastern face of Porcupine Mountain to the north of Swan River Valley, and in the Pasqui Hills still farther north, only the Campbell beaches are present (See Figures 1, 3, and 4). In this general region, and particularly along the eastern slope of Porcupine Mountain and west of Bowsman in Swan River Valley, numerous landslides have occurred, and in places have destroyed the beaches. Local ice masses appear to have remained on the Duck, Porcupine, and Pasqui Hills uplands after the main ice-sheet had retreated farther north, and to have prevented recording of the higher beaches. The position, however, of the main ice front at that time is not definitely known.

The ice border at the Campbell stage probably was at the Pas moraine, which extends for 20 miles along the railway southeast of The Pas, forms the ridge between Lake Winnipegosis and Cedar Lake, and continues east to Lake Winnipeg. The moraine was examined by the writer along the railway south from The Pas, and at places along the north shore of Lake Winnipegosis, where it is a broad ridge 50 to more than 100 feet above the lake.

Parts of a highland drift area in the southeast corner of Manitoba near Bedford and Woodridge are morainic(11). The highest beach near Woodridge has an elevation of 1,250 feet. It is 125 feet above the level of the Campbell beach in the vicinity, and probably is the highest Norcross beach (See Figure 5). Somewhat higher parts of the moraine appear not to have been covered by the lake. An ice border, therefore, may have existed at the moraine during one or more of the Herman stages. One or more of the Norcross beaches may extend to the northeast as far as Ignace (See Figure 2); and the ice border at that time may have stood at the Hartman moraine, which lies a few miles north of Dryden and Wabigoon, and, as seen from the railway, extends southeast to and beyond Ignace. The Campbell beaches may continue as far northeast as Sioux Lookout; and the moraines in that area may correlate with the Pas moraine, marking one of the most important ice borders of the lake.

DEFORMATION OF THE BEACHES

Isobases of the highest Herman, Campbell, and Burnside beaches can be drawn fairly accurately. Those numbered 1 to 4 on Figure 1 are isobases of the highest Herman and Campbell beaches; No. 5 is an isobase of the Campbell beach and approximately of the highest Herman beach; No. 6 is an isobase of the Campbell and Burnside beaches; and No. 7 is an isobase of the Campbell beach.

In preparing Figure 1, maps on 1 inch to 8 miles, and a general map on 1 inch to 35 miles, from which Figure 1 was made, were used. The elevations of the beaches were plotted on these maps, and lines (isobases) connecting points of equal elevation of the Campbell beach were drawn. As the beach in northern Minnesota and in the Rainy River district trends nearly in the direction of trend of the isobases, their location in that area is well defined. They show a marked change of course in the southeastern corner of Manitoba. Farther northwest they probably coincide with well-defined isobases of the Burnside beach. The tilt line normal to these isobases, one of which was later adopted as the 6th isobase, trends north $27^{\circ} 30'$ east, in the Rainy River district and in northern Minnesota, and about north 33 degrees east in the northern part of North Dakota and in southwestern Manitoba. By using these trends and drawing other isobases to the southwest in directions normal to these tilt lines it was found that the beach elevations on the western side of the lake fall very nearly on the same lines as do those on the eastern side, at equal distances to the southwest. It is probable, therefore, that these isobases have trends similar to that of the 6th isobase. The isobases shown on Figure 1 are those that were found to coincide with hinge lines when a profile of the beaches (Figure 2) was made. In this way the location of the hinge lines is shown. The hinge lines represent vertical planes passing through points of equal elevation of one or more beaches at places where there are marked changes in the rate of tilt of the beaches.

Figure 2 was first made by placing vertical lines indicating the position of isobases, at their respective distances apart, as shown originally on Figure 1, and plotting the elevations of the beaches at their respective distances normal to the nearest isobase. The location of the hinge lines was then apparent, and changes were made in Figures 1 and 2, so as to show only the isobases that coincide with hinge lines. It will be noted that many of the beach elevations, shown by dots on Figure 2, do not fall directly on the lines representing the beaches. This is due to the fact that beaches commonly vary a few feet in height from place to place. The fact that nearly all the elevations are very close to the lines indicates that the profile is a fairly accurate representation of the present position of the beaches; each beach was horizontal when it was being formed, and all of them have been deformed by earth crustal movements. It should be noted also that the vertical scale on Figure 2 is greatly exaggerated. This is necessary in order to show all the beaches; but it may give a false impression of the amounts of deformation, which are really very small considering the great distances involved.

Figures 3 to 5 are intended to show the locations of some of the beaches and the elevations of the beaches at different places. They were prepared on maps on 1 inch to $12\frac{1}{2}$ miles.

The isobases of all the beaches appear to have nearly the same trends, except possibly in the case of the Gimli and lower beaches, whose isobases may trend more towards the north. This is suggested by the fact that the tilt rate of this beach and that of the Grand Rapids beaches must be greater in the northern part of the Lake Winnipeg basin than that shown on Figure 2 in order to account for the amount of uplift, about 400 feet, that followed the post-Glacial marine submergence of the coastal region southwest of Hudson

Bay. It is possible also that hinge lines other than those shown on Figure 2 occur to the northeast, and that the tilt rate increases after continuing at a low rate for some distance.

There are at least seven hinge lines of deformation of the beaches. The first is a few miles south of the southern outlet, but has been only approximately located (See Figures 1 and 2). The others occur at irregular intervals to the north. The first and fifth are major hinge lines; the former marks the southern limit of the late Glacial uplifts; and the latter the limit, in the main at least, of the post-Glacial uplifts. The fifth hinge line (second major hinge line) coincides with or runs parallel with and near the 1,085-foot isobase of the Campbell beach. It passes near Greenbush, Minnesota, and near Arden, Manitoba. It extends from the region of Precambrian rocks on the southeast across an area of Palaeozoic formations, deeply drift covered for the most part, to the region of Mesozoic strata in the northwest; and passes through a low point of 800 feet in Red River Valley and a high point of 2,500 feet on Riding Mountain. There are thus no apparent topographical or geological features that might suggest that the location of the hinge line was influenced by a line of weakness. The absence of any such feature suggests that the earth crustal movements were very deep seated in origin. In addition to these normal hinge lines there may be lateral hinge lines trending in the direction of tilt and passing through points on the isobases where these show marked changes of course, as for example in southeastern Manitoba and to the southwest of that area (See Figures 1 and 5).

Figure 6 shows in profile the position of the highest Herman beach at various stages of deformation. It was constructed by estimating the amounts of deformation of the several beaches below the highest beach, and subtracting these amounts from the present altitude of the highest beach. This has been done in order to show the mode of deformation more clearly than can readily be seen by an inspection of Figure 2. In Figure 6 the highest beach is represented as extending to Ignace, Ontario, whereas it probably terminates south of the International Boundary. Its estimated altitude at Ignace, therefore, may be somewhat in error. It was assumed also in constructing the figure that the hinge line of no deformation, that is, the place where the beaches if extended to the south would become horizontal, was at the first hinge line for all the beaches down to the Stonewall, and at the fifth hinge line for the lower beaches. It is necessary to make this assumption in order to determine the amount of deformation of a beach at any particular place. The assumption may not be quite correct, as vertical uplift may have taken place and the tilting of some of the beaches may not have extended south as far as the first hinge line. The errors, however, are small and probably do not affect the general conclusions regarding the mode of deformation of the beaches.

An inspection of Figures 2 and 6 indicates that there were five periods of uplift, separated by times of comparative stability. The first period of uplift is shown by the splitting and divergence of the Herman beaches. It was initiated by a rapid uplift, amounting to about 20 feet, in the area north of the third hinge line. Uplift continued at a slower rate during the formation of most of the lower Herman beaches. The Norcross beaches mark a period of stability; they show little or no divergence to the north and are strongly developed. The next lower Tintah beaches show wide divergence. This indicates a rapid uplift, which may have continued well into the Campbell stage. As already pointed out, the Campbell beach probably marks a return of outflow to the southern outlet after a temporary diversion to the east. The uplift that began in the Tintah stage may have continued during the time of outflow to the east, and may have caused the return of outflow to the south. The Campbell beach marks a time of stability. This is shown by the great strength of the

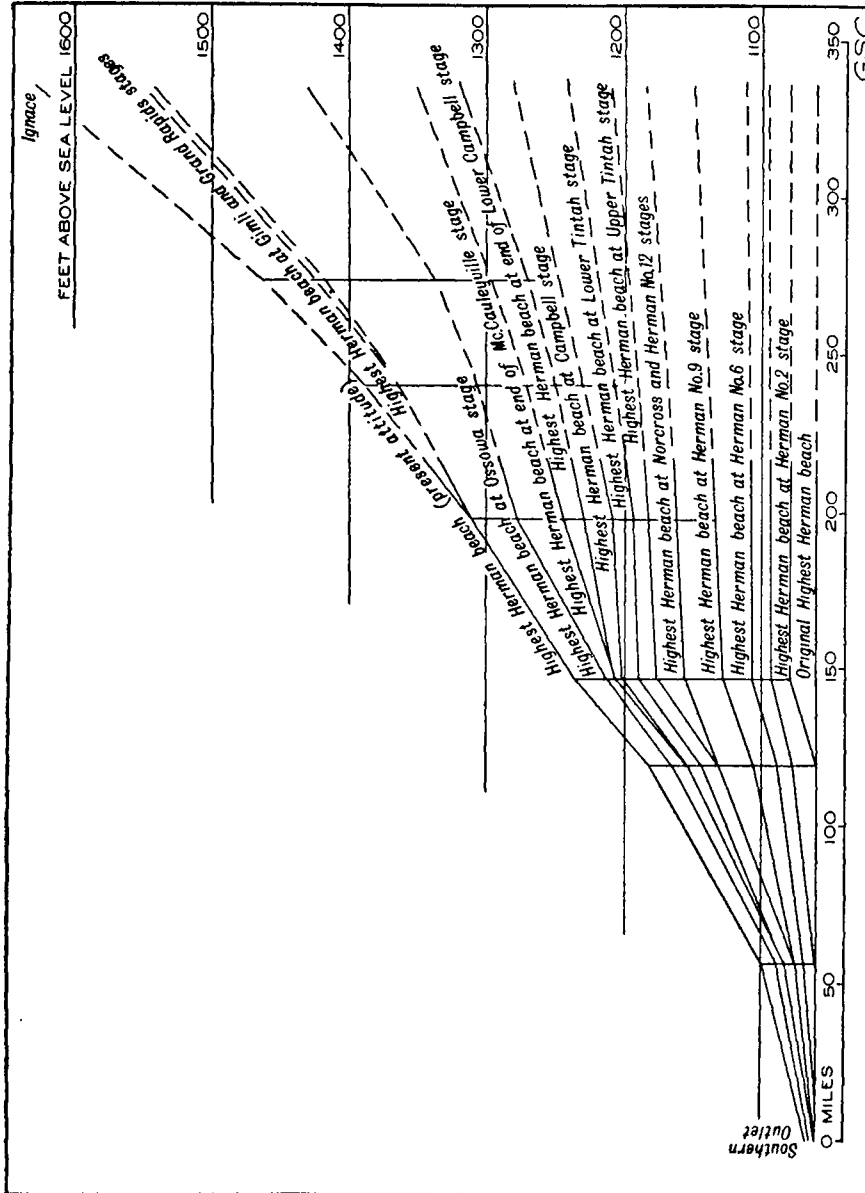


Figure 6. Profile showing position of the highest glacial Lake Agassiz beach at various stages of deformation.

beach in the north as well as in the south, and by the fact that it does not split to form a series of strands in the north.

A third period of uplift began during the Lower Campbell stage, and continued through part of the McCauleyville stage. The beaches below the McCauleyville, down to and including the Gladstone, are nearly parallel throughout their course, thus indicating a long period of comparative stability, during which the lake level was lowered about 150 feet by cutting down of outlets to the east, and opening of new outlets at progressively lower levels. During the first part of the period a small amount of land sinking took place in the south-central part of the lake basin. This is shown by the attitude of the Campbell and lower beaches in the vicinity of the fourth hinge line (Figure 2), where the greatest amount of sinking, perhaps 10 to 15 feet, occurred. Land sinking took place after transgression to the south of the strand line, and consequent deepening of the water in the southern part of the lake basin during the Lower Campbell and McCauleyville stages. Some sinking may also have occurred during the times of transgression of the shorelines. The deepening at the fourth hinge line was about 50 feet during the Lower Campbell stage, and was somewhat less during the McCauleyville stage. The sinking was a slow process; it continued during the formation of several beaches. There may have been other times of land sinking that are not recorded by the present attitude of the beaches.

The fourth period of uplift is indicated by the divergence of the Burnside and lower beaches down to and including the lower Pas. There was some uplift during the formation of the Burnside beach, but uplift nearly ceased for a time after its formation; the Ossowa and Stonewall beaches are nearly parallel to it. Uplift again continued during the formation of the lower Stonewall and Pas beaches, and following this uplift there was a period of stability that continued during the time immediately preceding the formation of the Gimli beach, when the lake was temporarily drained, and during the formation of the beach.

A fifth period of uplift began during the formation of the latest series of beaches, the Grand Rapids. It was the greatest of the uplifts, both in amount and extent, but was largely confined to the northern part of the lake basin and to the Hudson Bay region. It appears to have ceased in the Hudson Bay region some hundreds or one or two thousands of years ago, as there is no evidence of uplift within the past few hundred years at Churchill on Hudson Bay(3). The changes of level that have been going on in the Great Lakes region in recent years may be, in part at least, a land sinking similar to that which took place in the south-central part of the Lake Agassiz basin during the long period of comparative stability referred to above.

During the Herman uplift the first earth crustal movement appears to have been a vertical upthrust of a large block of the earth's crust, together with a tilting of a smaller block to the south, each block having been bounded by hinge lines. As uplift proceeded, areas farther south were affected, and the hinge lines shifted to the south. During succeeding periods of uplift areas progressively farther north were affected, and uplift proceeded in the same way, that is, it began in the north and gradually extended southward. There was thus a migration of hinge lines to the south as well as to the north.

During the Tintah uplift the first changes of level were in the north, as is shown by the mode of divergence of the Tintah beaches (See Figure 6). The first stages of the Lower Campbell and Burnside uplifts are not so clearly shown, because these shorelines were transgressive; and, therefore, the first lake stages are not recorded by beaches—the beaches first formed were destroyed or buried, except in the area near the eastern outlets, by the rising waters. The latest uplift, which began soon after the formation of the highest of the Grand Rapids beaches, appears to have started in the north, as is shown

approximately by the mode of divergence of the beaches in the Lake Winnipeg area (See Figure 2), and later to have affected the area to the south as far as the fifth hinge line.

The several uplifts appear to have lagged behind retreats of the ice-sheet; and times of stability may have coincided with or followed marked halts or readvances of the ice, but sufficient information is not available to definitely determine these questions. The lag in uplift following a retreat of the ice is most markedly shown by the great extent of the highest Herman beach. The fact that a lobe of the ice-sheet extended far south in the lake basin, as is shown by Leverett's mapping of the moraines in Minnesota, may have had some influence in causing a marked lag in the uplift; the ice may have remained in the central part of the lake basin while the lake spread far north along the sides, but uplift appears rather to have followed general depletion of the ice-sheet.

The comparatively high tilt rate of the lowest series of Lake Agassiz beaches in the southern part of Lake Winnipeg basin is of special interest. It is due to the progressive shifting to the north of the primary locus of uplift, and to the fact that the uplift, in the main, was limited by a hinge line not far to the south. In this way an explanation is afforded of the high rate of tilt of beaches, for example in the Ottawa Valley, at places well within the glaciated region. The explanation of such occurrences has long been a matter of speculation.

The amounts of uplift at places in the Lake Agassiz basin are shown approximately by the profiles of the beaches (Figures 2 and 6). The minimum amount at any place within the limits of the highest beach is the difference between the elevation of the beach on the isobase through that place and the elevation of the beach at the hinge line where the beach becomes horizontal. This is only a minimum amount, as the region of the zero isobase may have been broadly uplifted. This broad uplift probably was small in the area of the first hinge line, as the area is not far inside the border of the Wisconsin drift, and there is no reason to suppose that areas near the border were appreciably uplifted.

The total uplift at Ignace, Ontario, was nearly 600 feet. Of this amount about 250 feet are referable to the Herman and Tintah uplifts and 350 to later uplifts (See Figure 6). The ice border during the Herman stage was far to the southwest of Ignace, and during the Tintah stage probably was near Ignace or not far to the northeast. It is evident, therefore, that uplift took place in the area covered by the ice-sheet, at least near its margin, as well as in the area outside the margin. How far back beneath the ice the uplift continued is uncertain. The fact that uplift occurred in the area covered by the ice suggests that the total uplift in the Hudson Bay region may have been much greater than that indicated by the upper limit of post-Glacial marine submergence.

If the present conclusions regarding the mode of deformation of the Lake Agassiz beaches as set forth above, namely, vertical or broad uplift of large blocks of the earth's crust, and tilting of smaller blocks bounded by hinge lines; absence of warping except at hinge lines; and progressive, periodic shifting of the locus of uplift to the northeast towards the main centre of glaciation, are confirmed by future studies and are found to be applicable to other glaciated regions, they may be more in harmony with the theory of isostatic recovery following relief from the load of the ice-sheet than is the hypothesis of warping on a large scale. The present suggested mode of uplift differs from Hobbs' well-known hypothesis (6, p. 346) mainly in that there was migration of hinge lines to the south as well as to the north, and uplift was not continuous but occurred periodically.

In the present study of the Lake Agassiz beaches there are some features that bear a marked resemblance to those described by Sauramo in his admir-

able summary of "The mode of the land upheaval in Fennoscandia in Late-Quaternary time"(17). These include the occurrence of a major hinge line well to the north of the initial hinge line; a decrease in the tilt rate of some of the beaches towards the north; and the down sinking in the south-central part of the lake basin, which is somewhat similar to the "buckle" described by Sauramo.

CORRELATION OF LAKE AGASSIZ WITH THE GREAT LAKES

Periods of uplift separated by extended intervals of quiescence during the retreat of the last ice-sheet in the Great Lakes region have been described, and estimates made of their chronology, by Antevs (2). A tentative correlation of the times of uplift and stability in the Lake Agassiz basin with those in the Great Lakes region is shown in Table I.

TABLE I
Tentative Chronology and Correlations

Years ago	Lake Agassiz basin	Lake Agassiz beaches	Ice borders	Lower Great Lakes region (Antevs) ¹
0	5th stability			U
1,000				?
	5th uplift (greatest)	Grand Rapids		U
4,000				
	4th stability	Gimli		Q
6,500				
	4th uplift	Lower Pas Burnside		U
9,000				
	3rd stability (long) Local sinkings	Gladstone Blanchard		Q Sinking ? Q
13,000				
	3rd uplift	McCauleyville Lower Campbell	(Just south of Mattawa, Ontario)	U
16,000				
	3rd stability	Campbell	The Pas-Sioux Look-out moraines	
	2nd uplift	Tintah into Campbell		Q
	1st stability	Norcross and lowest Herman	Woodridge moraine	
20,000				
	1st uplift	Splitting of Herman		
23,000				U
	Beginning of Lake Agassiz	Highest Herman		
25,000				Q ?

¹ Late Quaternary Upwarings of Northeastern North America, by Ernst Antevs; Jour. Geol., vol. 47, No. 7, 1939, p. 719.

U=Upwarping of the land. Q=Quiescence, stability.

Regarding this correlation Antevs states (personal communication): "Since most geologists agree that the Mankato (Des Moines lobe) and the Valdres (ice border at Duluth, Port Huron morainic system, Buffalo, St. Johnsbury) maxima occurred roughly 25,000 years ago, Lake Agassiz began perhaps some 23,000 years ago. Dating and correlation of the first and second uplifts and stabilities are more or less guesswork. But from the third uplift there seems to be nice correlation with events in the Great Lakes region".

Transgressive shorelines similar to those in the Lake Agassiz basin have been noted in the Great Lakes region. One of them is indicated by "impounded shorelines" and has been described by Stanley(18).

Lake Agassiz at its highest stage, or at one or more of the high stages, may have been contemporaneous with Lake Algonquin in the Great Lakes region; the estimated amount of uplift at Ignace is the same as that indicated by the altitude of the Algonquin beach near Fort William on Lake Superior. The elevation of the Algonquin beach on McKay Mountain, near Fort William, is about 1,200 feet above the sea, as determined by Leverett and the writer, and, as the outlet at Port Huron is nearly 600 feet above the sea, the post-Algonquin uplift at Fort William was about 600 feet, the same as that at Ignace. The two places probably are nearly on the same isobase.

Lake Agassiz during the time of southward outflow may have been 375 to 450 feet above Lake Algonquin, as is shown by the difference between the levels of the respective outlets. At all stages it stood well above the Glacial and post-Glacial lakes in the Great Lakes region, so that drainage to the east could have occurred once the barrier of the ice-sheet was removed.

The average rate of tilt of the Lake Agassiz beaches is only about half that of the Algonquin and lower beaches in the Great Lakes region. This is probably due to the fact that the distance to the main centre of glaciation was less in the Great Lakes region than it was in the Lake Agassiz basin. The Patrician centre may have had some effect in causing increase of uplift in that area, especially in respect to the latest uplift; the tilt line of the latest uplift in the Lake Superior basin points to this local centre(12), and this may be the direction of tilt in southern Manitoba. In northwestern Manitoba the direction of tilt is more towards the Keewatin centre.

The first hinge line, a few miles south of the southern end of Lake Agassiz, may be the correlative of the Algonquin hinge line of no deformation near the Port Huron outlet of that lake, or of an earlier hinge line to the southwest. The fifth hinge line (second major hinge line) in the Lake Agassiz basin may extend across the Great Lakes to a point near the Trent Valley outlet of Lake Algonquin. This is suggested by its trend in the eastern part of the Lake Agassiz basin, and by the occurrence of an important hinge line, indicated by a marked change in the rate of tilt of the Algonquin beach, in the Trent Valley outlet area(5).

A feature that has an important bearing on the question of ice borders in the region between Lake of the Woods and Lake Superior, and is a very puzzling feature, is the occurrence of lake silt and clay at high levels along the Canadian Pacific Railway northwest of Fort William. These deposits extend northwest from Lake Superior across the present divide to Savanne, 72 miles to the northwest. They occur up to 1,585 feet above the sea, 100 feet above the upper limit of Lake Agassiz sands at Ignace, 76 miles farther to the northwest. They probably are deposits of Lake Duluth, a predecessor of Lake Algonquin in the Lake Superior basin. If so, the area in which they occur must have been free of ice while an ice lobe extended far to the south in the Lake Agassiz basin, for there are no comparable Lake Agassiz deposits for a long distance southwest of Ignace. Lake Agassiz at its highest stage probably was at least 200 feet above Lake Duluth, but whether the two lakes were contem-

poraneous is not known. If they were, Lake Agassiz must have covered a very small area in the south, whereas Lake Duluth extended far to the north. The great depth of Lake Superior may have had some influence in causing floating and consequent melting of the ice in the western part of the basin, thus forming a deep re-entrant in the ice-sheet during its general retreat. During the Lake Duluth stage the eastern part of the lake was occupied by the ice-sheet (12). A northerly trending ice front in the western part of the lake is suggested by the occurrence of westerly bearing striæ at Port Arthur. The striæ, as noted by the writer but not previously recorded, occur in a park on the lake shore in the eastern part of the city.

The silts and clays west of Fort William were long ago known to Frank B. Taylor, who regarded them tentatively as deposits of Lake Algonquin (19). Their occurrence doubtless influenced him in placing the ice border of the lake far to the north in the northwest corner of the Lake Superior basin.

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